COMPUTER SIMULATION IN UNIVERSITY TEACHING

Proceedings of the FEoLL Workshop

28-30 January, 1980

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FOREWORD

This book gives a survey of contributions presented at the workshop concerning the problems of computer simulation in university teaching. This workshop was arranged on January 28-30 by the "Institut für Bildungsinformatik", which is one of the departments of the FEoLL GmbH (Research and Development Center for Teaching and Learning Procedures) in Paderborn (Federal Republic of Germany), in collaboration with the Physics department of the Catholic University of Louvain (Belgium).

"Bildungsinformatik" (Educational Computer Science) should be understood both as a field of practical work and as a scientific paradigm of its own. It is concerned with analysing and even more with synthesising the heterogeneous network of education and computer science, two phenomena which interact very much in today's society. Therefore "Bildungsinformatik" is found in an intermediate position between educational practice and the correlates of educational sciences (especially systems, structures and processes) on one hand, and applied computer science and theoretical computer science, on the other hand. A fundamental and current idea which connects the fields of education and computer science is the reduction of complexity. In this foreword we want to give some suggestions about this connection.

Not only the educational system but also computer science has the problem to be affected by an increasing complexity. Computer science as new scientific discipline, which has grown up from electronic data processing, is having one foot in the field of structural sciences (logics, mathematics) and the other foot in technological sciences (e.g. electronics). Simplified one could understand its method as a synthesis starting with single elements of operation and decision, and ending in complex systems formulated by a hierarchy of artificial languages. Soft- and hardware systems of that kind can be understood as models of general systems which can be found in nature, society or in human intelligence.

The method of simulation enables us to introduce various parameters into the models and to make experiments with models. Thus numerous aspects of empirical or experimental sciences can be treated in the frame of computer science. Using the method of simulation we can either partially substitute the original system by a computer simulation or give deeper insight into the behaviour of the original system. The variation of parameters in the simulation system allows the optimation of the system's conformity with the real world, and allows us to set up hypotheses for modified complex systems, which cannot be effectively done by other methods. Together with systems theory and technology, computer science is offering an efficient methodological tool to master complexity. This stresses the importance of simulation as a methodological tool. We hope that the ideas presented in the workshop will help forthcoming progress on this fascinating field of research.

PROFESSOR DR. MILOS LÅNSKÝ

PREFACE

The contributions of this volume are not explicitly put into separated paragraphs or sections, as it would have been very difficult to make clear distinctions about who is covering theoretical or general reflections on modelling and simulations, who is describing design ideas for programming simulations, or who is evaluating the students' work with his programs. Therefore the papers are more or less in the sequence they were presented at the workshop. Starting with contributions which contain greater parts of theory on modelling and simulation, then several contributions with different aspects of learning through computers. These are followed by examples of simulations with detailed descriptions of which we have first gathered a block of physics examples as those were the most numerous.

DETLEF WILDENBERG

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In the area of Computer Assisted Learning it is useful to make an operational distinction between simulation and modelling. I will assume that simulation allows the student to control input parameters and observe the output while modelling allows the student to control or change the model upon which the simulation is based. This approach will be illustrated with examples from Physics in which a change in the model results in a corresponding change in the solution algorithm, in which iterations represent the passage of time. An example will also be discussed which enables simple models of a predator-prey situation to be developed. The algorithm requires iterations of the growth cycle and predicts the variation of the two populations.

INTRODUCTION

Scientists have been making use of digital computers for more than two decades. Their use is increasing on an ever widening front, particularly as technological developments in hardware progressively reduce the cost of computers and computing power is more readily available through multi-access terminals. The existence of computers should therefore be acknowledged by science teachers who are training the next generation of professional scientists. One of the obvious tasks facing us is in the training of young scientists in the sensible and creative use of computers; as well as in the teaching of when *not* to use computers. The computer's influence rests on three intrinsic qualities:

1. Information in various forms can be stored and readily present to a student.
2. Information can be manipulated by the computer.
3. The student can be made to respond to the information presented through the need to answer questions or input data when requested.

These qualities make the interactive computer a powerful tool for actively involving the student in his learning and giving the student numerical experience.

The computer presents the teacher with two options, providing the student with Computer Assisted Learning (CAL) material that is pre-programmed (package) and expecting the student to program the computer himself. These two aspects of CAL will be discussed below.

SIMULATION AND MODELLING

In the area of Computer Assisted Learning it is useful to make an operational distinction between simulation and modelling. I will assume that simulation allows the student to control input parameters and observe the output as illustrated in figure 1. The model, usually in the form of a mathematical relationship, is set up within the computer program and the student can simulate the phenomena or process by controlling the input and observing the output.

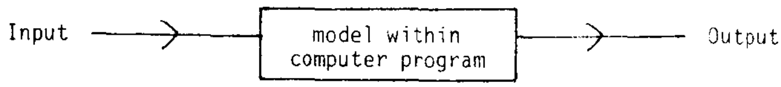

Figure 1

Schematic diagram of the simulation process

In modelling the student is able to control or change the model upon which the simulation is based as illustrated in figure 2. Tawney [1] has discussed in detail working definitions of simulation and modelling.

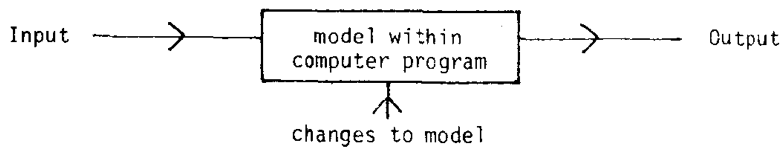

Figure 2

Schematic diagram of the modelling process

SIMULATION PACKAGES

Simulation packages are of particular value for topics which are mathematically complicated and for which it is difficult for students to comprehend the full range of behaviour just from the mathematical formalism. The computer can thus be used to deepen insight into a physical phenomenon. Packages have also been developed to simulate laboratory situations where real experiments would be dangerous, time-consuming, expensive or technically difficult. A number of simulation packages have been developed by the Physics Department at Surrey covering such topics as the transmission of electrons through a potential barrier, the conductivity of semi-conducting materials and radioactive decay chains. A full list is available and some examples are given below which illustrate various facilities and techniques that are available using VDU terminals.

An example of the simulation of a process that is mathematically complicated and that could not be demonstrated in a laboratory is that of the transmission of electrons through a potential barrier. A program called TRANS calculates the transmission coefficient for electrons incident upon a potential barrier. The effect of varying the electron energy and the barrier width is determined and the output data is presented in tabular form.

The objective is for the student to study the dependence of the transmission coefficient upon various parameters and thereby understand the physical importance of these parameters. In choosing numerical values for the various parameters the student gains experience in choosing values sensibly in order to locate turning points and other features asked for in the student notes. A sample output of this program is illustrated in Appendix 1.

An example of presenting information in a simplified graphical form on a VDU is illustrated below in a package called MOCOIL which simulates a moving coil meter and calculates the displacement when a current passes by solving the appropriate differential equation. The first part of the package uses a tutorial approach to make the student correlate the various terms in the differential equation with the physical processes and to relate the resultant behaviour with the mathematical restrictions placed on the parameters in the equation. For a given choice of parameters the output is presented in simple graphical form as well as tabulated at the side, as illustrated in Appendix 2.

The variation of a parameter over a two dimensional surface can readily be illustrated as a density map. For example a package TRIPLOT maps the potential distribution due to three point charges. The objective is to familiarize students with the field patterns around various charge distributions such as a monopole, a dipole and a quadropole. An example is illustrated in Appendix 3.

Familiarity with a *method of representation* of a physical system can readily be gained through a simulation package that emphasises the method of representation.

One such example is in tensor notation. A package STRAIN investigates the behaviour of elastic deformation in two dimensions defined by four tensor components. The objective is to familiarise the student with the concept of a tensor quantity, the decomposition of strain into dilational and deviatoric components and the conditions under which second order terms may be neglected. This program tries to make the student think critically about the input and output of data in the package by asking him to anticipate the output corresponding to the values he has chosen for the input parameters. This is done using multiple choice questions and by requesting a numerical estimate and is illustrated in Appendix 4.

An example of the simulation of an experiment occurs with a package called COUNTERS. This package simulates a radiation experiment and enables optimisation of the experimental arrangement of detectors, sources and geometry. The objective is for the student to gain skill in experimental strategy and familiarity with the significance of various counting techniques. A large number of simulated experiments can be carried out in an hour which would in the real laboratory take many days. A sample output from the program is illustrated in Appendix 5. Other examples of laboratory experiment simulations have been reported by Masterton [2].

In all of the packages discussed above the essential feature that makes them different from any alternative method of presenting the same information is their interactive nature. It is the student who determines, through his interaction, what will appear on the terminal. For this interaction to be meaningful it is essential that the student must remain an active participant and this can be achieved if the student is set a definite task, the successful completion of which depends upon the purposeful use of the simulation program, which in turn may depend crucially upon a well written students' guide.

Implicit within any simulation porgram is the model, expressed in mathematical or computational terms, upon which the physical simulation is based. The student should be aware of the model but usually has no opportunity or facility for changing the model.

MODELLING PACKAGES

There have been few packages reported in the literature which give students the opportunity of modelling through changing the model. One example by Bork [3] in a CAL program called MOTION provides the opportunity for the student to change the inverse square law of gravitational attraction, which would result in unstable gravitational orbits.

Another method of trying to make students aware of the model is to set up a simulation in which the students are not told the model but by controlling input and observing output they are asked to determine the model by a process of induction. Hebenstreit [4] has described such a simulation program in which students have to determine the law of reflection. The program simulates the motion of an elastic projectile moving in a horizontal plane and rebounding from a vertical wall. The aim is to hit a given point in the plane after reflection from the wall and thereby induce the law of reflection.

Bork and Robson [5] devised a program to simulate wave propagation along a string in which students can *observe* how a string behaves and then try to predict how it will subsequently behave, thereby *discovering* the characteristics of wave propagation. Students were expected to induce Stokes' law from a simulation of spheres falling in viscous fluids in a program devised by Montgomery [6]. In all of these modelling-simulation programs students were expected to gain some insight into the concept of modelling and some training in inductive thinking, but it is reported that they have all been of very limited success.

THE ALGORITHMIC APPROACH

The familiar form in which models are described in science depends very heavily upon analytical mathematics and in particular *the calculus*. Indeed every branch science has depended upon the calculus for its advance since the 18th Century and the calculus has influenced the way in which we teach science. Peckham [7] and others have suggested that a computing facility by its intrinsic numerical nature gives a tool of a new kind to the student in problem solving and in the development and description of models. It is a tool based on the algorithm; the sequence of precisely defined steps by which a problem is solved. The algorithm removes most of the restrictions on the types of model that can be proposed and explored. The computer enables the student to develop simple solution algorithms which enable the characteristics of the model to be explored and thus the model can be changed or modified and the resultant effect studied.

Thus to solve a problem algorithmically requires firstly a very clear understanding of the problem and a very precise statement of its step by step solution. This is an intellectual exercise through which the student gains a better understanding of the physics of the problem and gains the important high-level skill of developing algorithms. This process is illustrated in Figure 3 and is examplified by a comment by a student:
'Programs are aimed at specific goals and in preparing a program one is constantly asking the question, what exactly do I do?'

PROBLEM ⟶ ALGORITHM ⟶ PROGRAM ⟶ RESULTS

Heuristics *Programming* *Execution*

Figure 3

Schematic diagram of the algorithmic process

SIMPLE PROBLEMS

Let us consider solving the simple problem of the harmonic oscillator. The equation of motion for a particle of mass m subjected to a linear restoring force is:

$$m\frac{d^2x}{dt^2} + kx = 0 \qquad (2)$$

where x is the displacement, t is time and k the force constant. This differential equation leads to an analytical solution:

$$x = B_1 \cos \omega t + B_2 \sin \omega t \qquad (3)$$

where $\omega^2 = k/m, \quad B_1 = x_0 \quad B_2 = v_0/\omega$

where x_0 is the initial displacement and v_0 the initial velocity.

Equation (3) represents the displacement x as a function of time. This is a very compact and elegant representation and we can say this is a *solution* to our problem. But in fact this is only a solution because it is known from experience what is meant by the cosine and the sine function. In fact, if a specific use of our analytical solution is required the cosine and the sine at a particular value might have to be evaluated.

The analytical mathematics required by the student to perform the analysis outlined above is really quite complicated, and further there is no direct correspondence between the various steps in the analysis and the physics of the problem once the equation of motion and the initial conditions have been established, whereas in an algorithmic approach each step in the solution has a direct correspondence with the physical process as indicated below.

Now if a computer is available it is possible to go directly from the initial statements of the problem to the numerical solution, using an algorithmic approach. This is elegantly set out by Peckham [8] in a very useful book on computational techniques for physics. The problem is thus transposed into finding an algorithm to solve equation (2). The equation can be rewritten as two first order equations:

$$\frac{dx}{dt} = v \qquad \frac{dv}{dt} = -\frac{k}{m}x. \qquad (4 \& 5)$$

Using the Euler method the solution algorithm is

$$x_2 = x_1 + v_1 \delta t \qquad (6)$$

$$v_2 = v_1 - \frac{k}{m} x_1 \delta t \qquad (7)$$

where suffix 2 refers to the new value and 1 to the old value. Setting initial values to x_1 and v_1 the variation of x with t can readily be computed iteratively. The advantage to this method of solution is that there is close correspondence between the physics that governs the motion of the particle and the solution algorithmic. Equation (6) clearly represents an increment of displacement due to a velocity existing for an interval of time δt. Equation (7) can be seen as an impulse of force acting for an interval of time to change the velocity. No further complicated operations are required to obtain the solution as indicated in the computer print out which is listed together with the computer program in BASIC in Appendix 6. The table is a solution to the original problem. It is not exact, far from it, but simple improvements in the computational technique can lead to accuracy of any desired level as illustrated in figure 4 which shows a computer plot of x versus t.

The extension of the above solution to a problem of increased complexity is straightforward. Thus if a resistive or frictional term is to be added to the equation of motion this can readily be accommodated by adding the appropriate term to the algorithmic solution in equation (7). In the approach illustrated above the

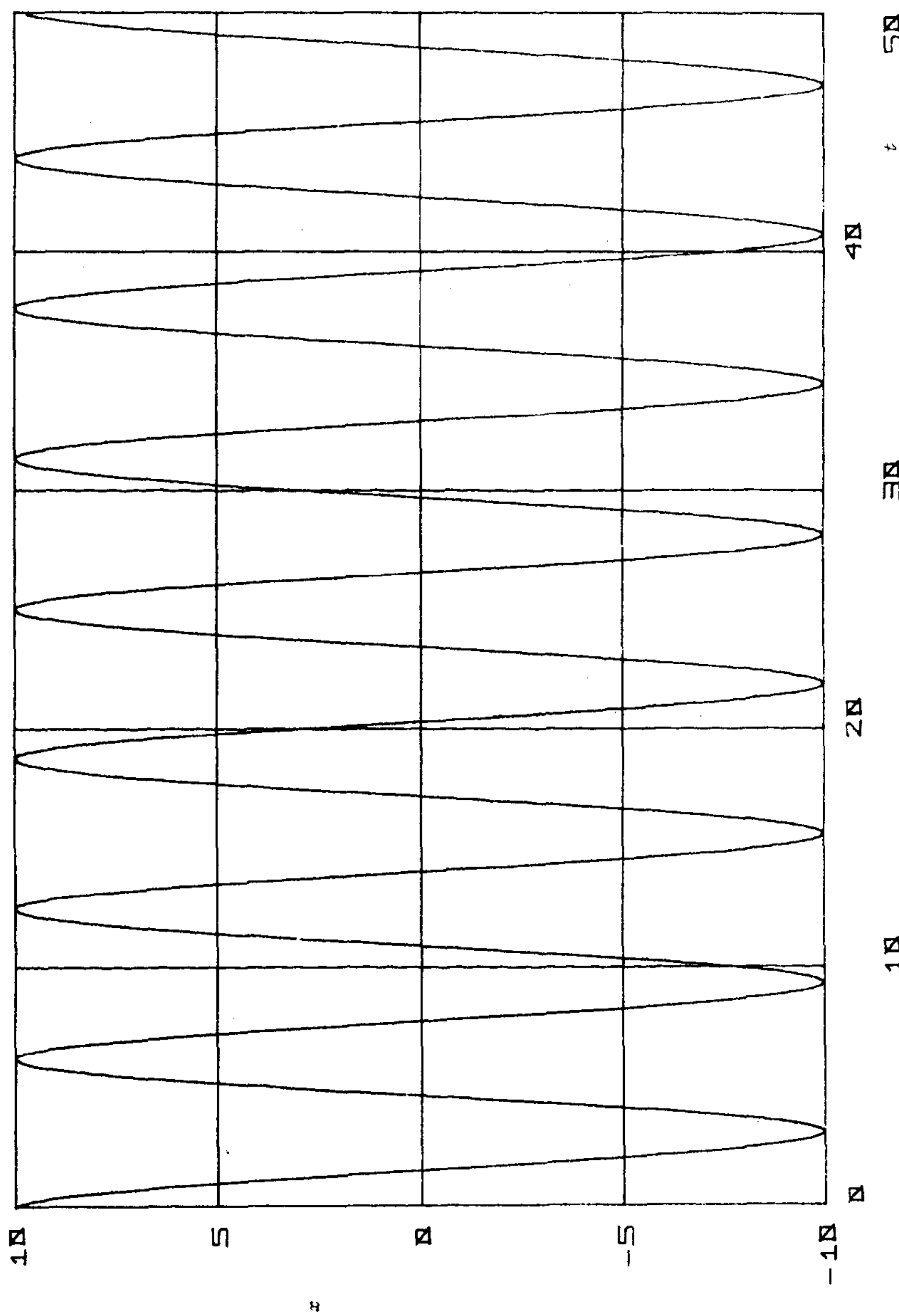

Figure 4

Plot of displacement x against time t

student must concentrate his efforts on the formulation of the problem and the interpretation of the results and not be distracted by the analytical feasibility of a solution. In other words there are two routes to solve the problem: a traditional analytical one and a numerical or computational one. It is not being suggested that the traditional method should be abandoned. On the contrary, it may be that the numerical route to solving a problem can throw insight on to the analytical route.

COMPLEX PROBLEMS

The real value of the numerical approach is in solving complex problems where the model ceases to be sufficiently simple for analytical techniques to be available. Such problems arise from consideration of realistic situations which have not been artificially simplified. This occurs particularly when considering practical applications of physics. However the model must be precisely understood by the student if he is to be able to produce an algorithm for solving the problem.

Let us consider a problem that is outside normal analytical techniques: the calculation of the magnetic field due to a current loop. The standard case is the calculation of the field on the axis of the current loop. The analysis is simplified by the symmetry of the problem but it is not usual for a textbook to comment that the reason the field off-axis is not to be considered is that it cannot be calculated analytically, even though for many practical applications the field off-axis must be known. However the computer enables the student to solve the problem by numerically carrying out the line integral.

The Biot-Savart law can be expressed as

$$\vec{dB} = \frac{\mu_0 I}{4\pi r^3} \vec{dl} \times \vec{r} \tag{8}$$

where dB is the element of magnetic induction at a point P due to the element of wire dl carrying current I distance r from point P, as illustrated in Figure 5. The total field at point P can be obtained by carrying out the line integral of equation (8). Numerically this approximates to a summation. The essential steps in the algorithm are establishing the relationship between the components of the vector quantities involved. Thus the line element δl can be written as three components:

$$\delta l_x = 0, \quad \delta l_y = -\delta l \sin\theta, \quad \delta l_z = \delta l \cos\theta \tag{9}$$

where δl is the length of the element δl and is given by

$$\delta l = a\delta\theta \tag{10}$$

where a is the radius of the loop.

The radius vector r can be written as the difference between coordinates of point $P(x_2,y_2,z_2)$ and the element $\delta l(x_1,y_1,z_1)$. Thus

$$r_x = x_2 - x_1, \quad r_y = y_2 - y_1, \quad r_z = z_2 - z_1 \tag{11}$$

The cross product $\delta l \times r$ can thus be readily evaluated in terms of its components and hence the element of magnetic field expressed in components, for example

$$\delta B_x = \frac{\mu_0 I}{4\pi r^2}(l_y r_z - l_z r_y) \tag{12}$$

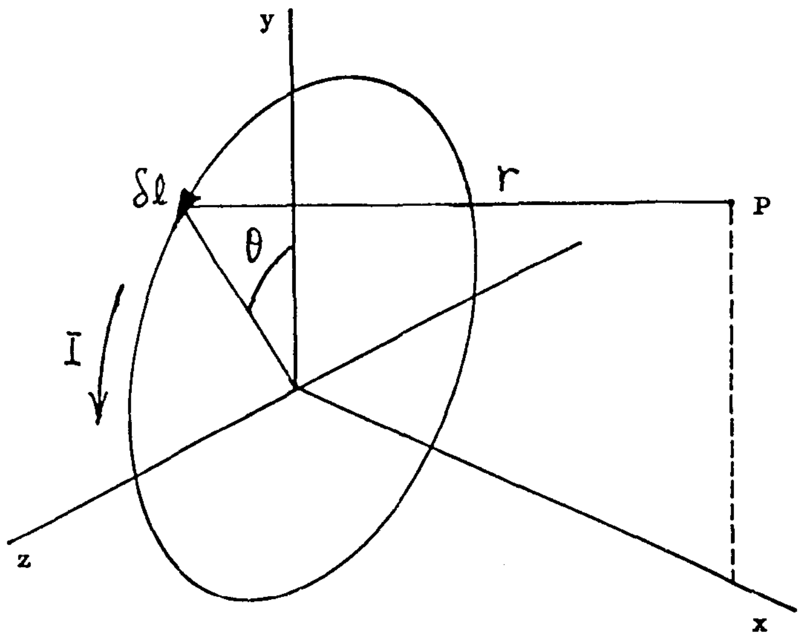

Figure 5

Magnetic Field due to Current Loop

Thus by using three components for each vector the operations are reduced to simple numerical computations.

Hence the resultant field components are

$$B_x = \Sigma\delta B_x, \quad B_y = \Sigma\delta B_y, \quad B_z = \Sigma\delta B_z \tag{13}$$

the summation being carried out for $\theta = 0$ to $\theta = 2\pi$. The resultant field is then

$$B = [B_x^2 + B_y^2 + B_z^2]^{\frac{1}{2}} \tag{14}$$

However due to the symmetry of the coil about the x-axis $B_z = 0$. Hence the field direction is given by

$$\phi = \arctan\,(B_y/B_x) \tag{15}$$

where ϕ is the angle in the x-y plane. A BASIC program to calculate the magnetic induction at any point in the x-y plane is listed in Appendix 7. The program was used in conjunction with a plotting facility to generate the magnetic field map shown in Figure 6.